FAILURE MECHANISMS

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LONGITUDINAL TENSION

- FAILURE MODES

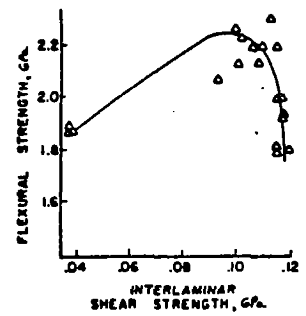
WEAK MATRIX

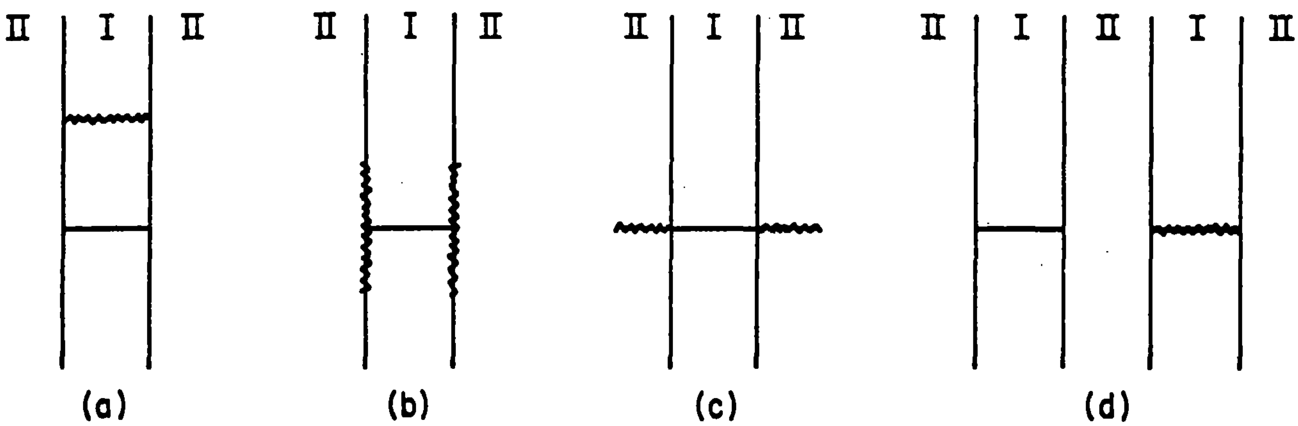
WEAK INTERFACE

OPTIMUM

STRONG MATRIX

STRONG INTERFACE

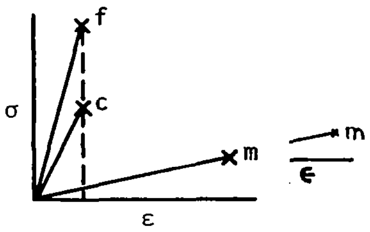




CRACK GROWTH MODES IN UNIDIRECTIONAL COMPOSITES

- PREDICTION OF STRENGTH

RULE OF MIXTURES

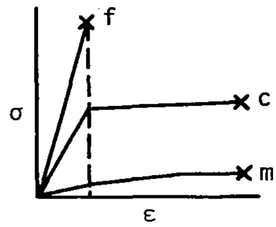


BRITTLE MATRIX

$$X_L = (v_f + v_m E_m/E_f)X_f$$

MINIMUM FIBER VOLUME FRACTION

$$v_f = \frac{E_f}{E_f - E_m}\left(\frac{X_m}{X_f} - \frac{E_m}{E_f}\right)$$



DUCTILE MATRIX

$$X_L = v_f X_f + v_m X_m$$

- BUNDLE STRENGTH

FIBER STRENGTH DISTRIBUTION

$$R(X_f) = \exp\,[-L(X_f/X_{fo})^{\alpha}]$$

$$R(Y_f) = \exp\,[-L(Y_f/Y_{fo})^{\alpha}]$$

$$X_{fo} = E_f Y_{fo}$$

AVERAGE FIBER STRENGTH

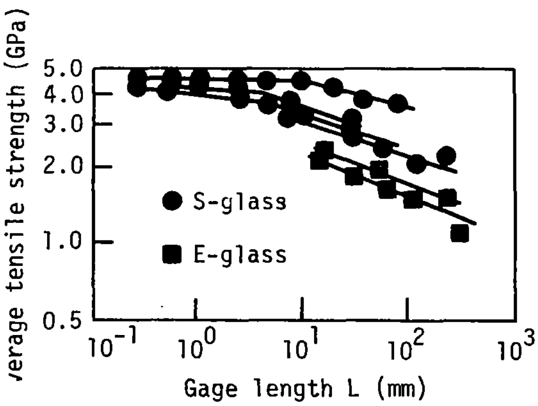
$$\overline{X}_f = X_{fo}\, L^{-1/\alpha}\, \Gamma(1 + 1/\alpha)$$

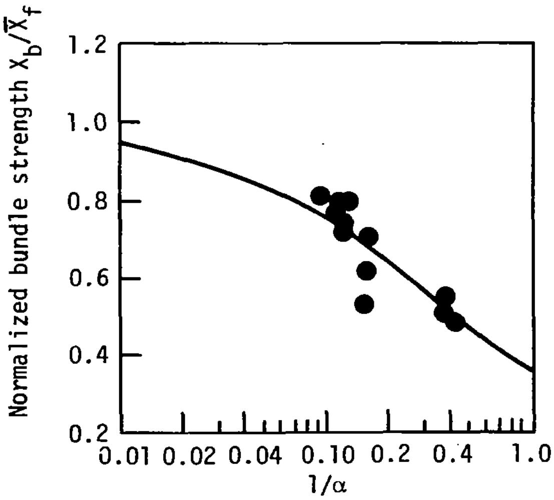
BUNDLE STRENGTH

$$X_b = X_{fo}\,(L\alpha e)^{-1/\alpha}$$

BUNDLE-TO-FIBER STRENGTH RATIO

$$\frac{X_b}{\overline{X}_f} = \frac{1}{(\alpha e)^{1/\alpha}\,\Gamma(1 + 1/\alpha)}$$

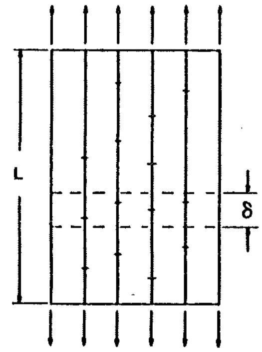




- OPTIMUM STRENGTH

$$X_L = v_f X_b(\delta) + v_m \bar{\sigma}_m^{\,*}$$

$$\frac{X_b(\delta)}{\overline{X}_f(L)} = \frac{1}{(\alpha e)^{1/\alpha}\,\Gamma(1 + 1/\alpha)} \left(\frac{L}{\delta}\right)^{1/\alpha}$$



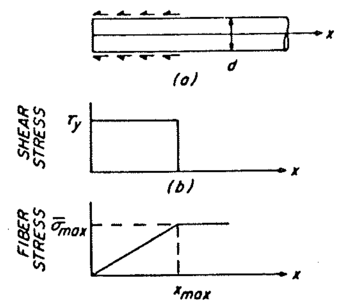
INEFFECTIVE LENGTH OR
LENGTH OF FAILURE INTERACTION ZONE

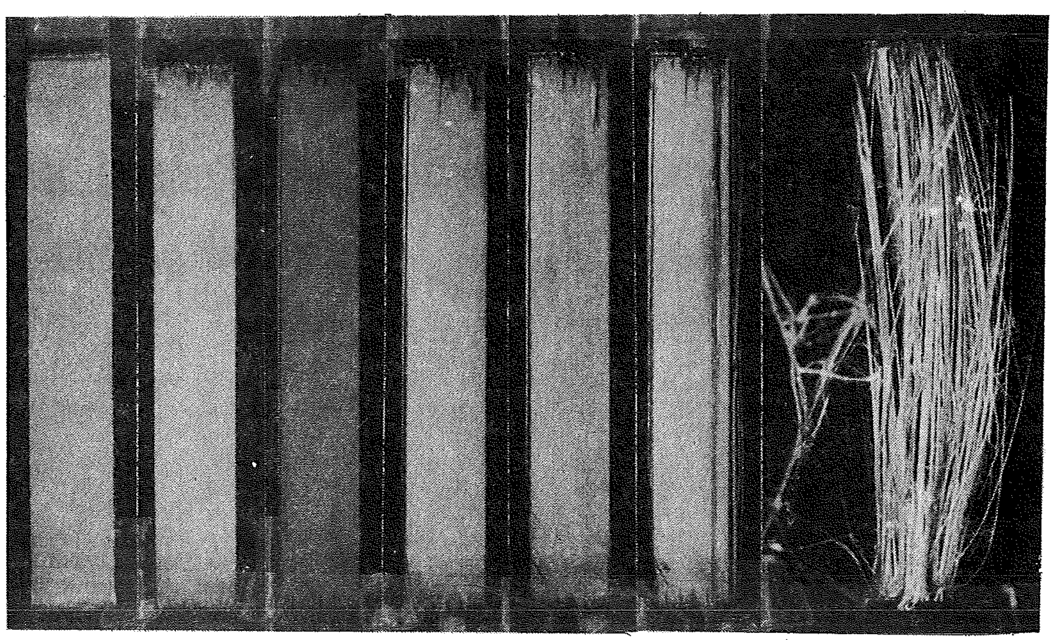
$$\frac{\delta}{d} = 2\left(\frac{\overline{X}_f}{4\tau_y}\right)^{\alpha/(\alpha+1)} [(\alpha+1)L/d]^{1/(\alpha+1)}$$

IF $\alpha >> 1$, RULE OF MIXTURES

$$\frac{\delta}{d} = \frac{\overline{X}_f}{2\tau_y}$$

$$X_L = (v_f + v_m E_m/E_f)\,\overline{X}_f$$



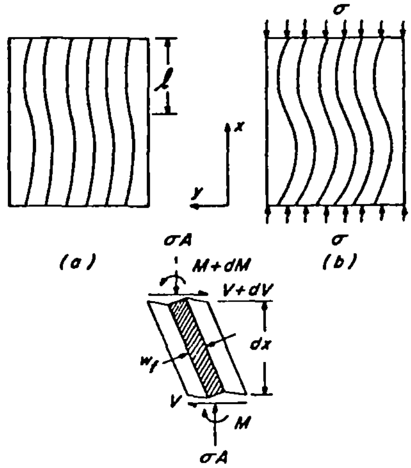


Stress, %UTS 0 45 72 86 94 99 100

Static failure sequence for Kevlar 49/epoxy

LONGITUDINAL COMPRESSION

• MICROBUCKLING OF FIBERS



INITIAL DEFLECTION

$$v_o = f_o \sin \frac{\pi X}{\ell}$$

FINAL DEFLECTION

$$v = f \sin \frac{\pi X}{\ell}$$

COMPRESSIVE STRESS

$$\sigma = \left[G_L + \frac{\pi^2}{12} v_f E_f \left(\frac{w_f}{\ell}\right)^2 \right] \left(1 - \frac{f_o}{f}\right)$$

$$\approx G_L \left(1 - \frac{f_o}{f}\right)$$

• COMPRESSIVE STRENGTH

$$X'_L = G_L \left(1 - \frac{f_o}{f_c}\right)$$

LOCAL SHEAR FAILURE

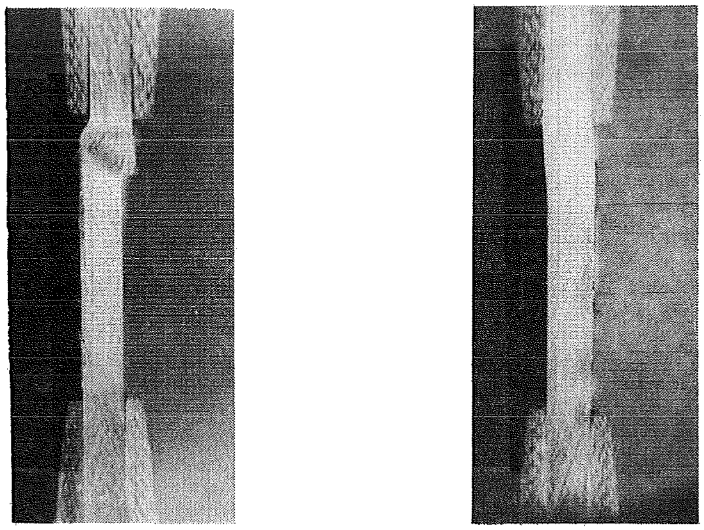
$$f_c = f_o + \frac{\ell}{\pi} \frac{X_S}{G_L}$$

FLEXURAL FAILURE OF FIBER

$$f_c = f_o + \frac{2\ell}{w_f} \frac{\ell}{\pi^2} \frac{X_f}{E_f}$$

FINAL STRENGTH

$$X'_L = G_L \frac{1}{1 + (\pi f_o/\ell)/(X_S/G_L)}$$



Shear type Buckling type

Compression failure mode for Gl/Ep

TRANSVERSE TENSION

• ELASTIC PREDICTION

$$(\sigma_m)_{max} = (SCF)\ \overline{\sigma}_2$$

$$X_m = (SCF)\ X_T$$

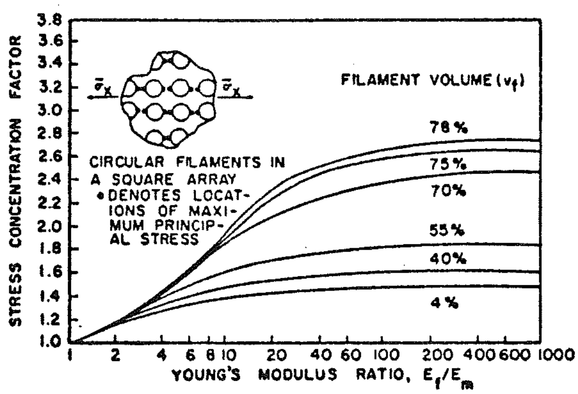
$$\frac{X_T}{X_m} = \frac{1}{SCF}$$

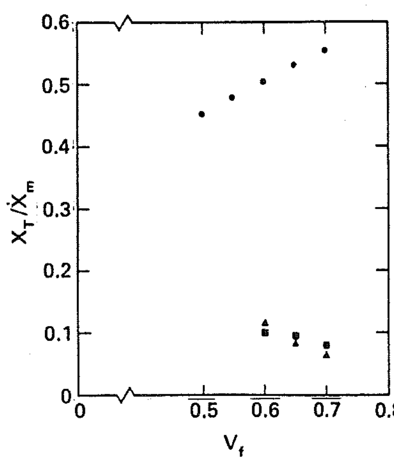
$$SCF \uparrow \text{ AS } \frac{E_f}{E_m} \uparrow$$

$$SCF \uparrow \text{ AS } X_m \downarrow$$

$$\frac{X_T}{X_m} \downarrow \text{ AS } X_m \downarrow$$

USE X_{int} IF INTERFACIAL FAILURE





MATRIX DUCTILITY

$$X_T = v_f\bar{\sigma}^*_{f2} + v_m\bar{\sigma}^*_{m2}$$

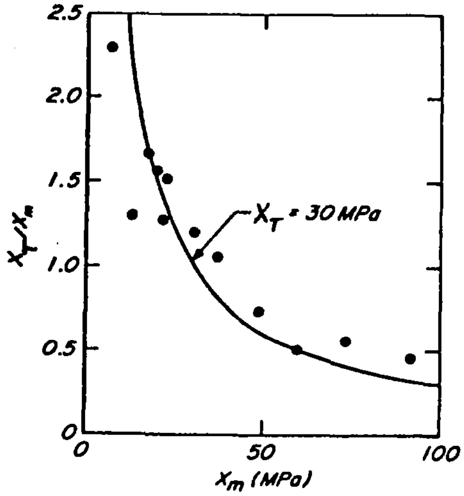
$$= (v_f/\eta_2 + v_m)\,\bar{\sigma}^*_{m2}$$

$$K_{m2} = (\sigma_m)_{max}/\bar{\sigma}^*_{m2}$$

$$\frac{X_T}{X_m} = \frac{1 + v_f\,(1/\eta_2 - 1)}{K_{m2}}$$

$K_{m2} \uparrow$ AS $X_m \uparrow$

$\frac{X_T}{X_m} \downarrow$ AS $X_m \uparrow$



TRANSVERSE COMPRESSION

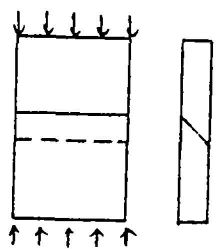
FAILURE PLANE

~ 45° INCLINED

X'_T/X_T

4 ~ 7

~ X'_m

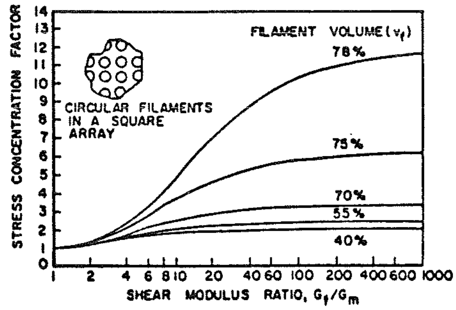


LONGITUDINAL SHEAR

ELASTIC PREDICTION

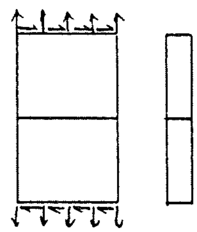
SAME AS X_T

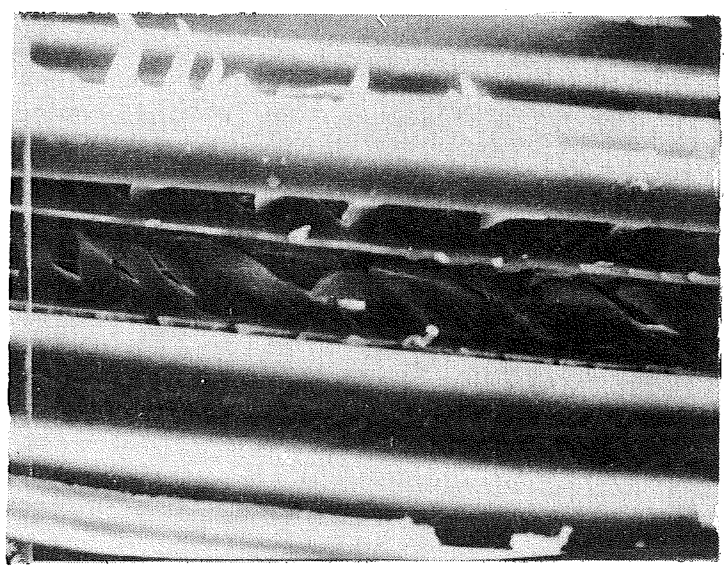
$$\frac{X_S}{S_m} = \frac{1}{SCF}$$

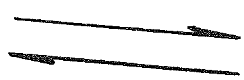


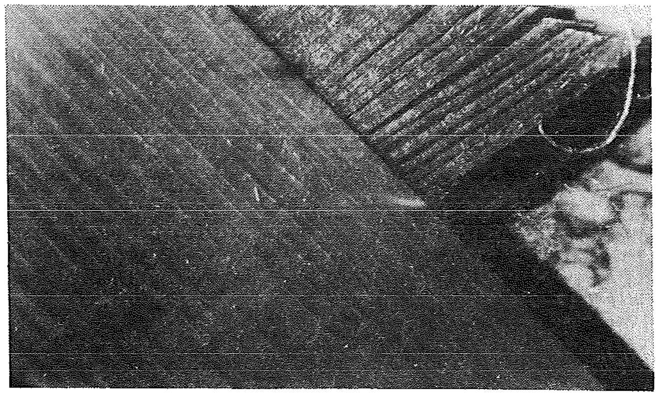
MATRIX DUCTILITY

$$\frac{X_S}{S_m} = \frac{1 + v_f(1/\eta_6 - 1)}{K_{m6}}$$









macroscopic

Shear failure for Kevlar 49/Ep

LAMINA FATIGUE

LONGITUDINAL TENSION

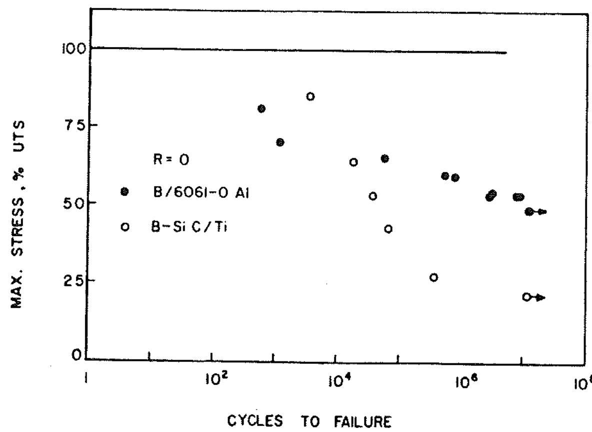
MATRIX-CONTROLLED FAILURE LIKELY

FATIGUE LIMIT STRAIN OF MATRIX ≈
FATIGUE LIMIT STRAIN OF COMPOSITE

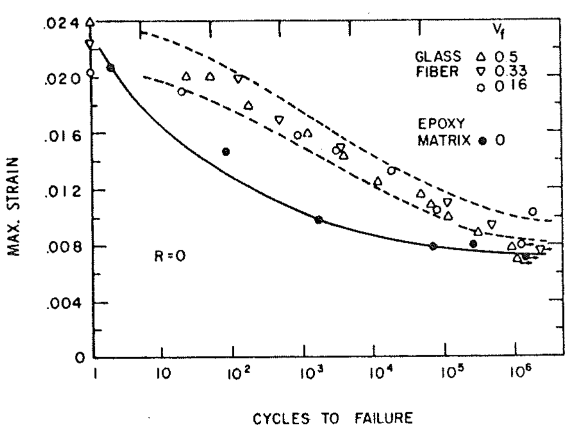
FATIGUE LIMIT STRESS

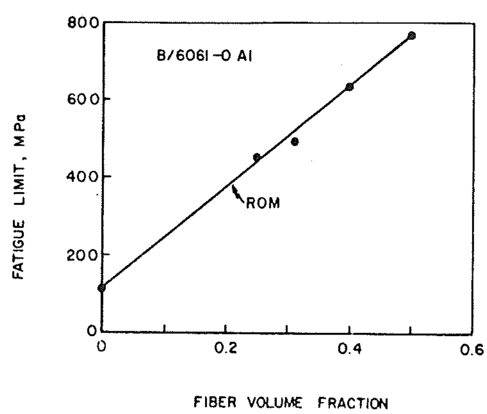
$$S_{FL} = S_{mFL} + v_f(E_f/E_m - 1)\, E_m \varepsilon_{FL}$$

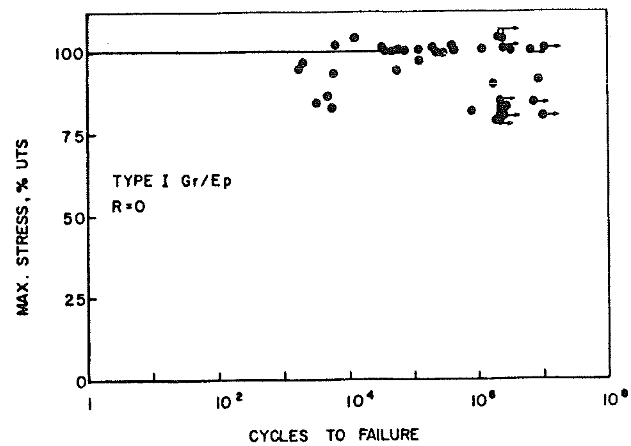
LOW FATIGUE SENSITIVITY IF FATIGUE LIMIT STRAIN > STATIC FAILURE STRAIN OF FIBER



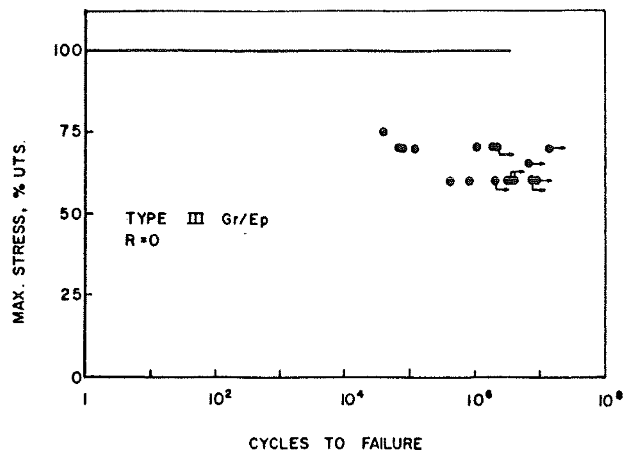
Longitudinal S-N data for B/Al and B-SiC/Ti (Ultimate tensile strength - 1698 MPa for B/Al and 1296 MPa for B-SiC/Ti)



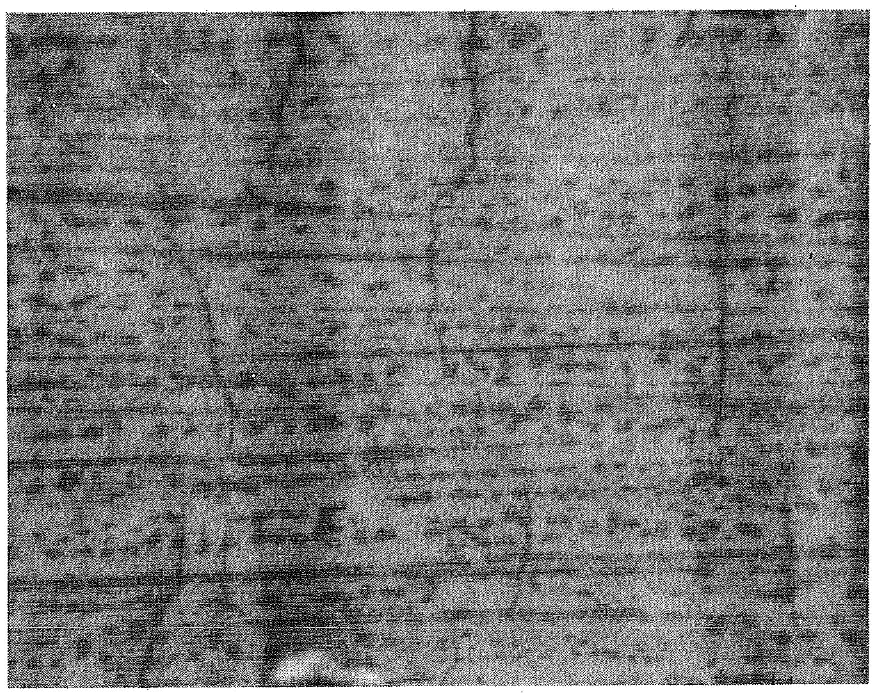


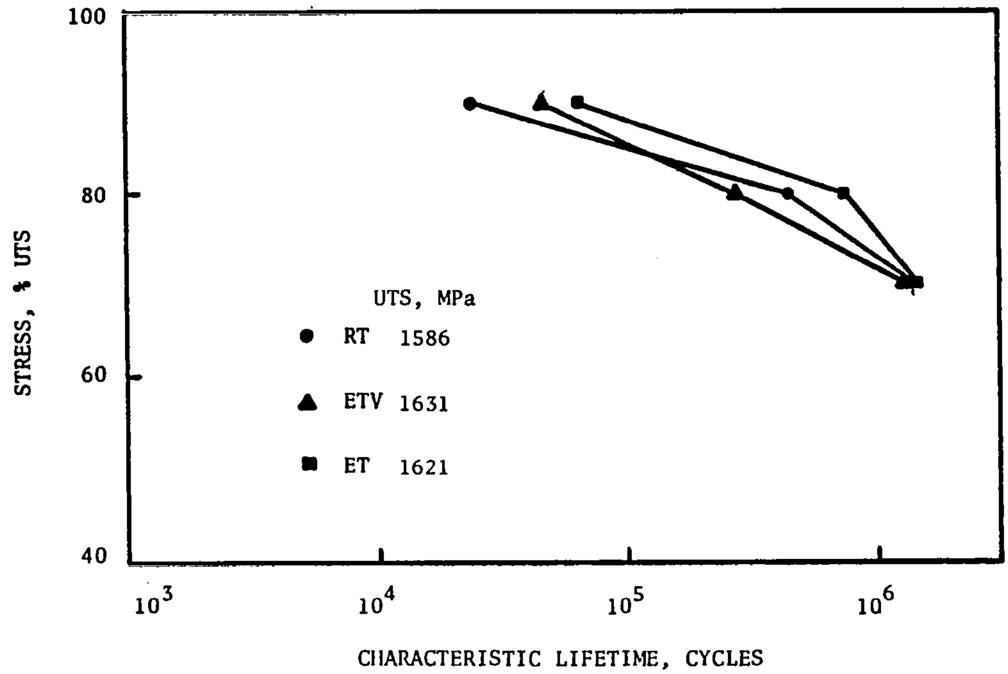


TYPE I Gr/Ep
R=0
MAX. STRESS, % UTS
CYCLES TO FAILURE

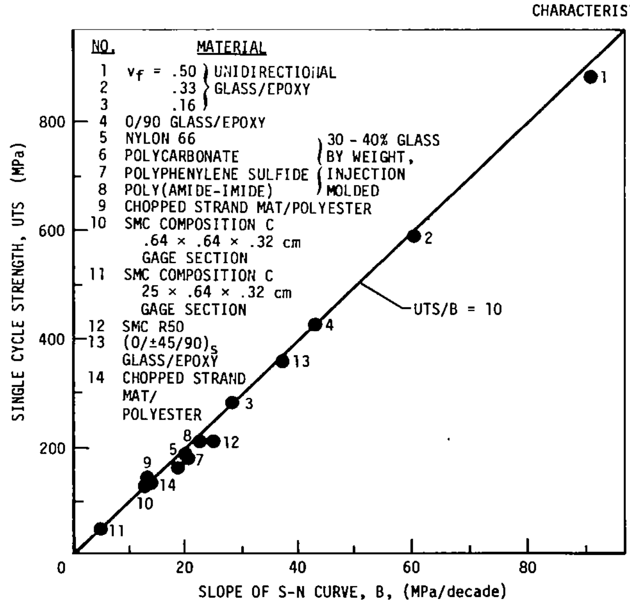


TYPE III Gr/Ep
R=0
MAX. STRESS, % UTS.
CYCLES TO FAILURE

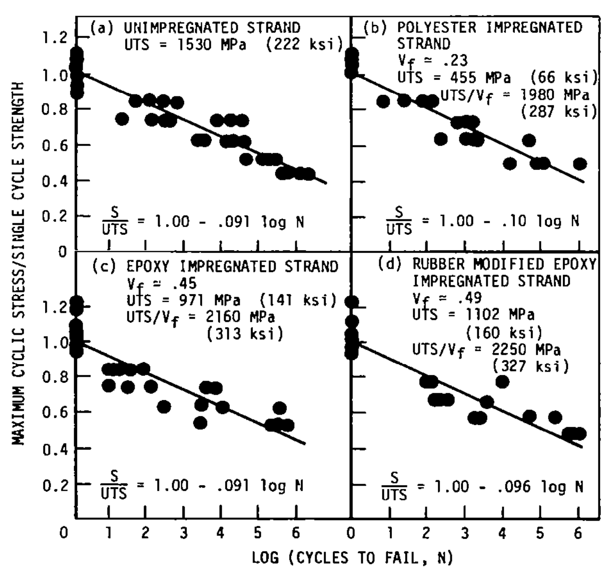




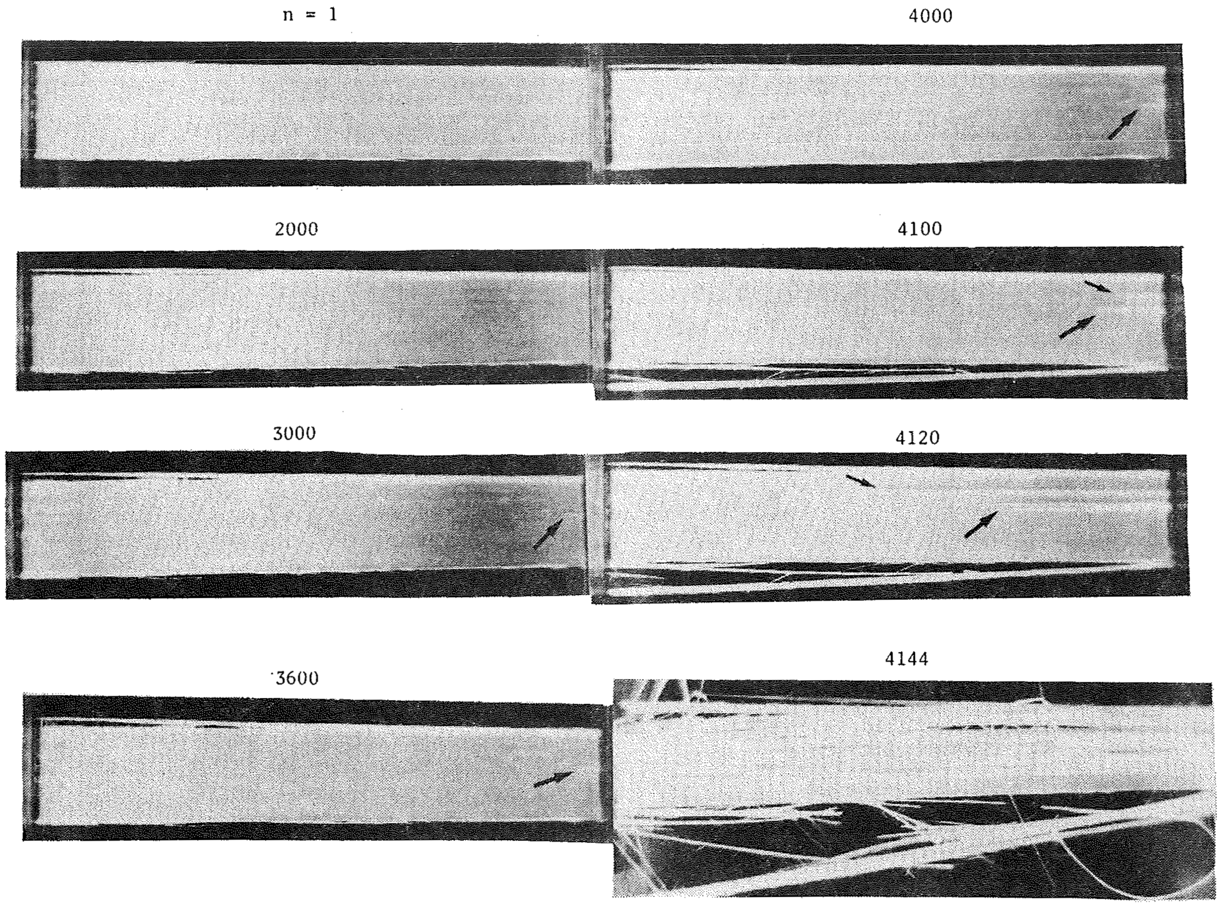
CHARACTERISTIC FATIGUE LIVES



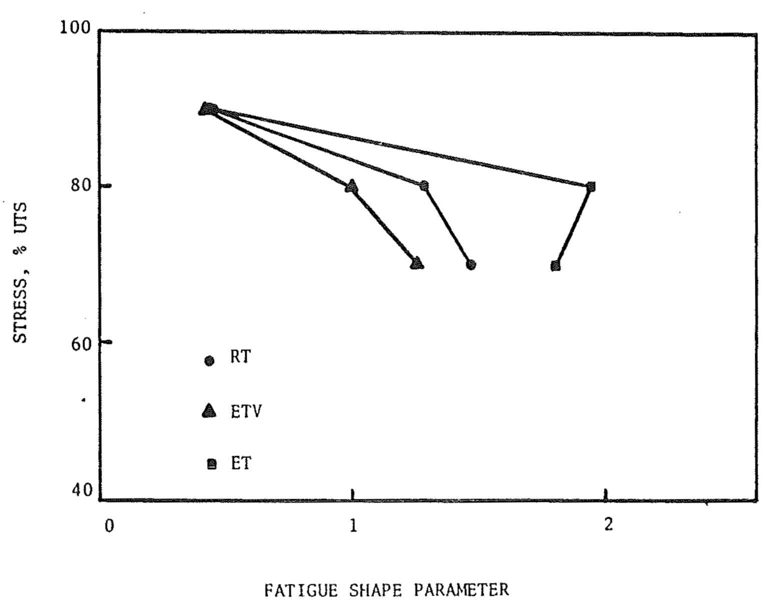
Single cycle strength versus slope of S-N curve, nonwoven glass fiber composites, tension-tension fatigue at R = 0 to 0.1



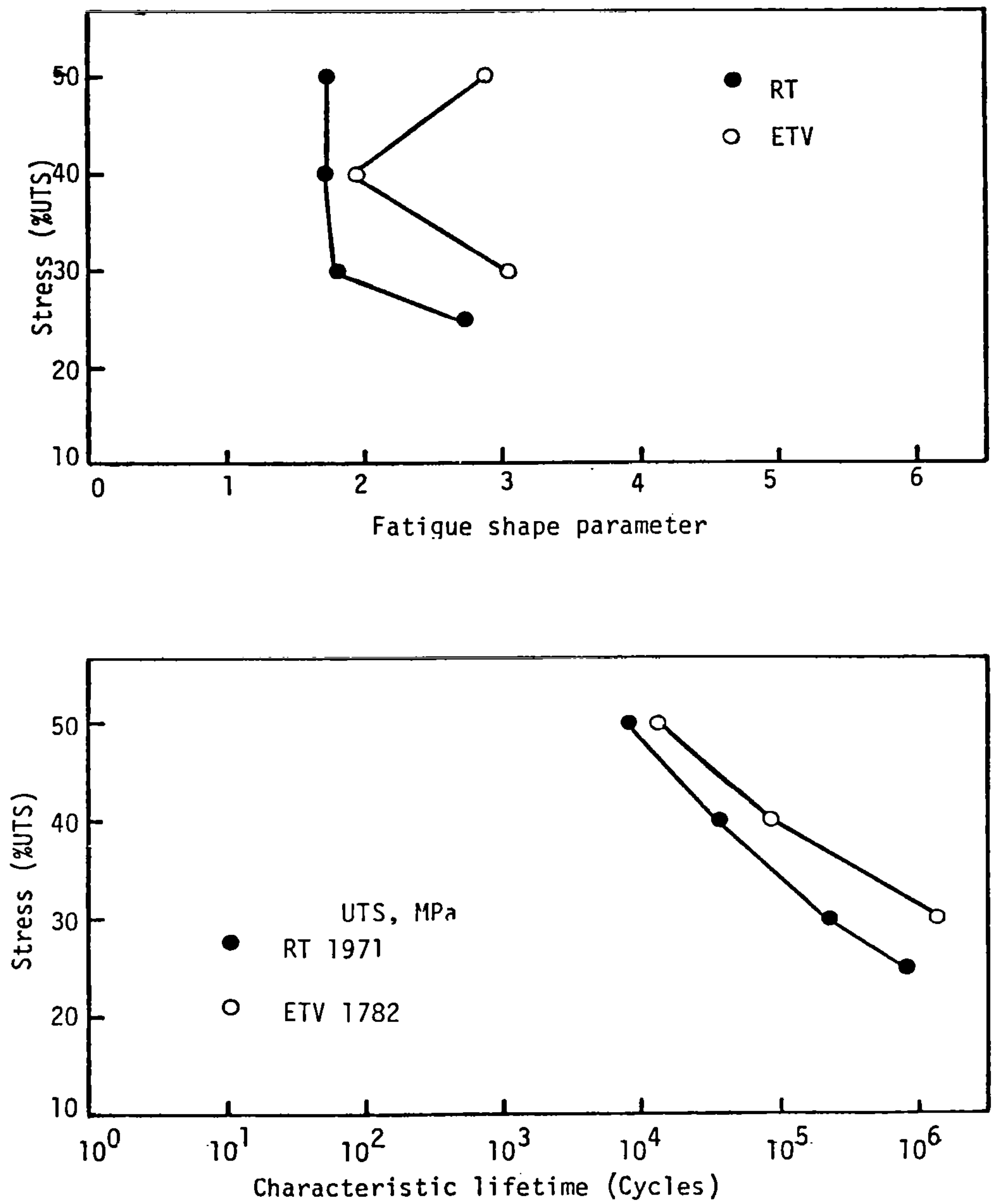
Normalized tensile fatigue life curves for E-glass strand without matrix and with several matrices (5 Hz, R = 0.10).



Fatigue failure process at 60 percent UTS, RT, Gl/Ep



Fatigue shape parameters



Weibull parameters for fatigue life distributions

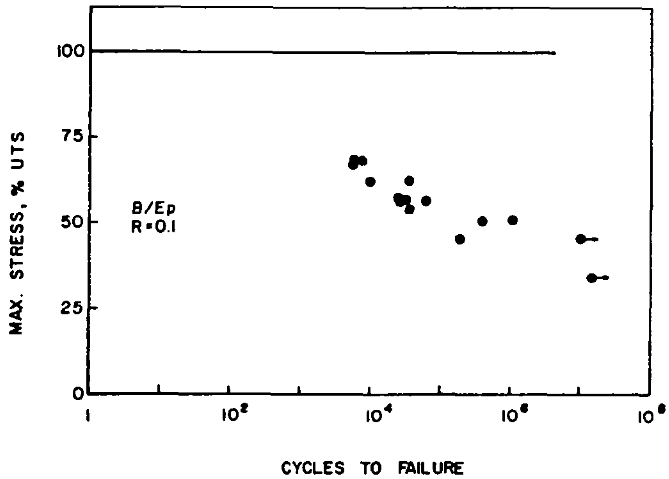
• TRANSVERSE TENSION AND LONGITUDINAL SHEAR

HIGHLY FATIGUE SENSITIVE

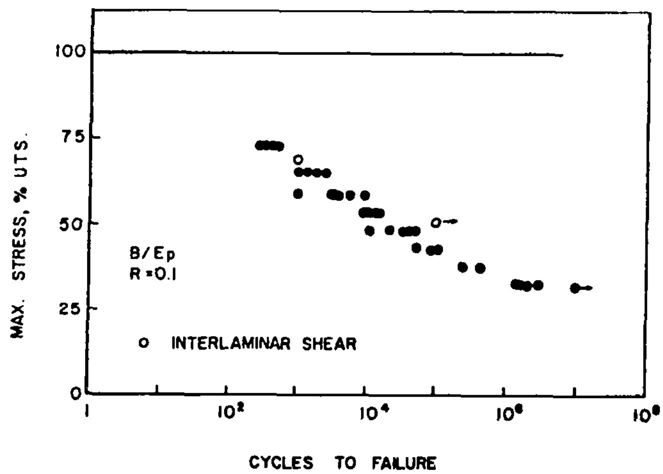
MORE THAN 60% REDUCTION IN STRENGTH AT 10^6 CYCLES

FAILURE RESULTING FROM FAST CRACK PROPAGATION

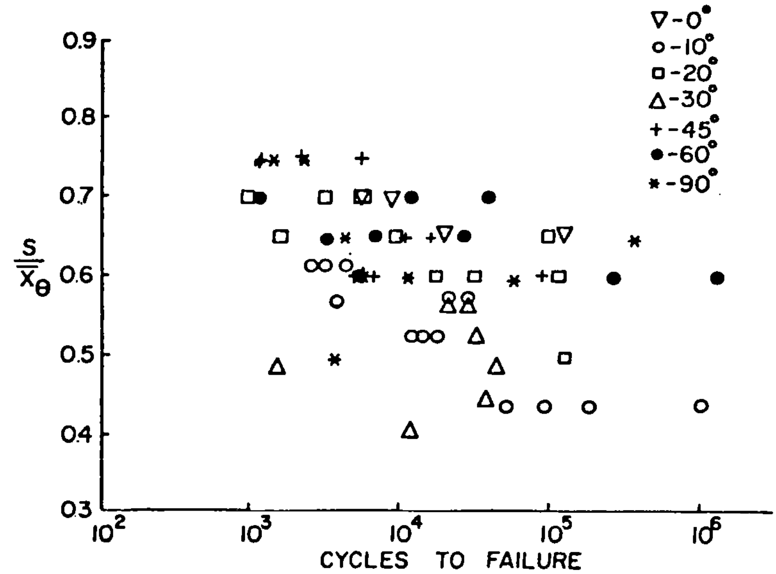
NO INDICATION OF GRADUAL CHANGES IN MODULUS AND STRENGTH



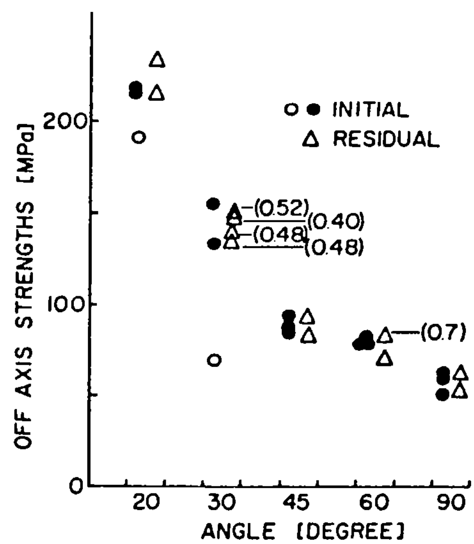
Transverse S-N data for B/Ep (Ultimate tensile strength = 60.9 MPa)



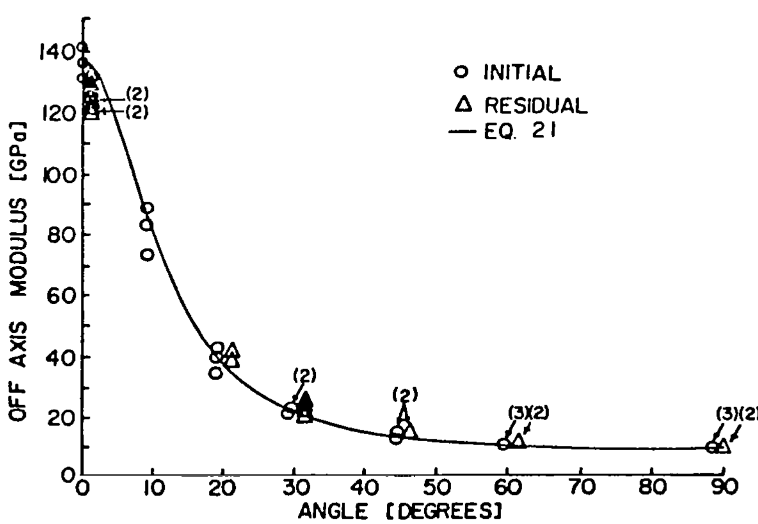
Shear S-N data for B/Ep. (Longitudinal shear strength = 66.7 MPa, interlaminar shear strength = 81.4 MPa)



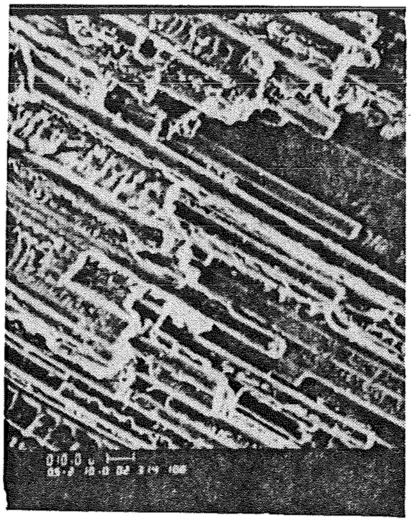
∇-0°
o-10°
□-20°
Δ-30°
+-45°
●-60°
*-90°
$\frac{S}{X_\theta}$
0.9
0.8
0.7
0.6
0.5
0.4
0.3
10^2
10^3
10^4
10^5
10^6
CYCLES TO FAILURE



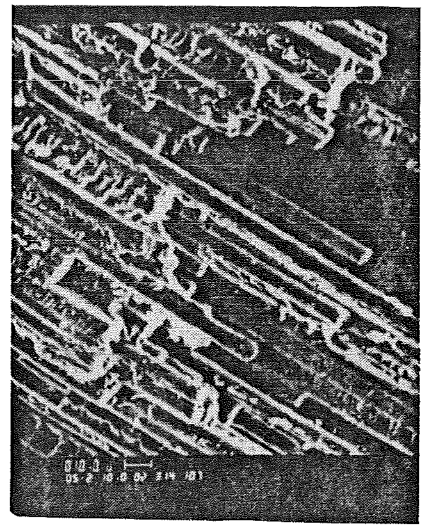
o ● INITIAL
Δ RESIDUAL
OFF AXIS STRENGTHS [MPa]
200
100
0
(0.52)
(0.40)
(0.48)
(0.48)
(0.7)
20
30
45
60
90
ANGLE [DEGREE]



o INITIAL
Δ RESIDUAL
— EQ. 21
OFF AXIS MODULUS [GPa]
140
120
100
80
60
40
20
0
(2)
(2)
(2)
(2)
(3)(2)
(3)(2)
0
10
20
30
40
50
60
70
80
90
ANGLE [DEGREES]



LEFT

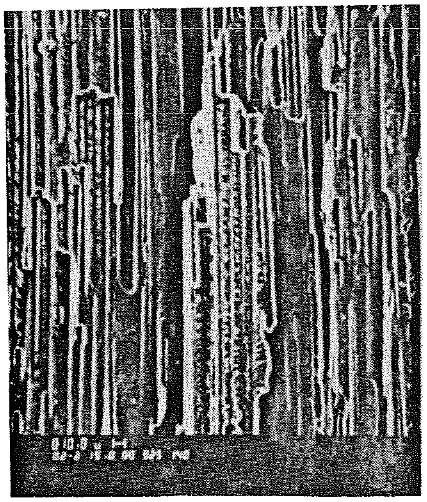


RIGHT

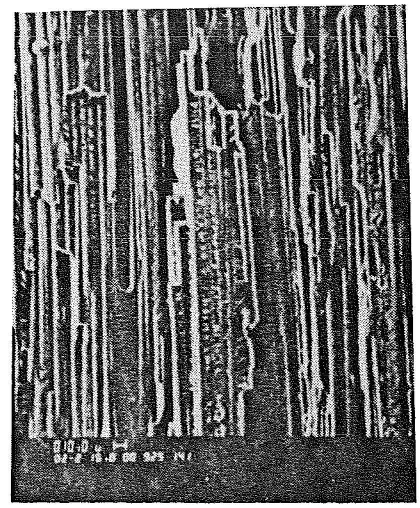
30^{o}

LEFT

RIGHT

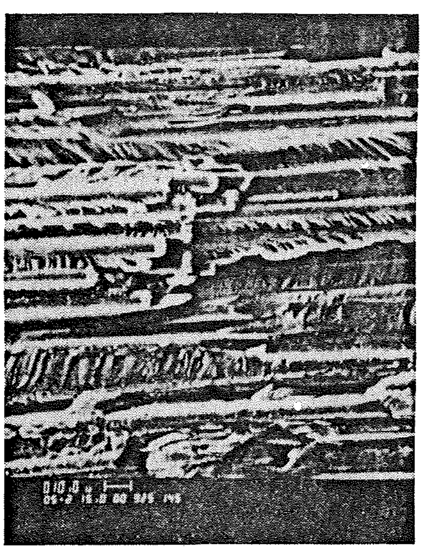


LEFT

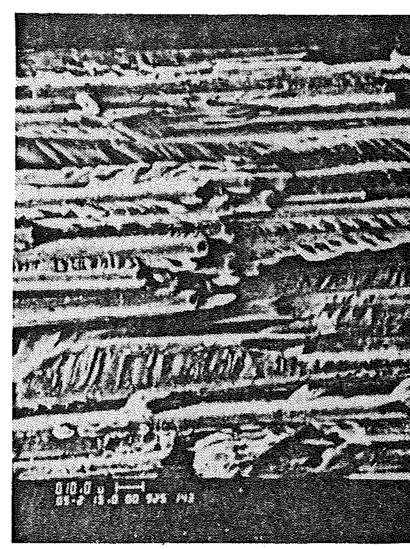


RIGHT

90^{o}



LEFT



RIGHT

LAMINATE FATIGUE

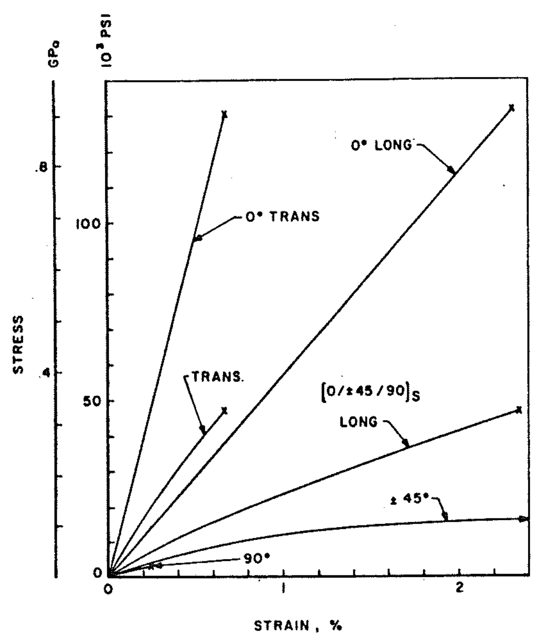
FAILURE PROCESSES

FIRST PLY-FAILURE

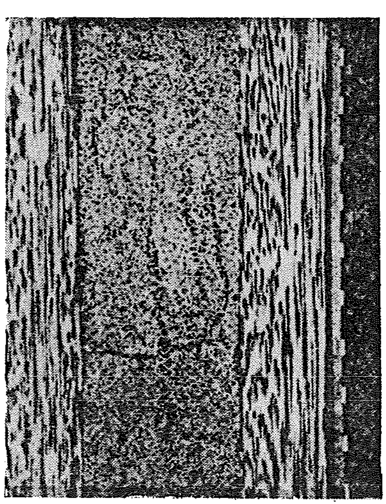
ASYMPTOTIC INCREASE IN CRACK DENSITY IN PLIES

DELAMINATION

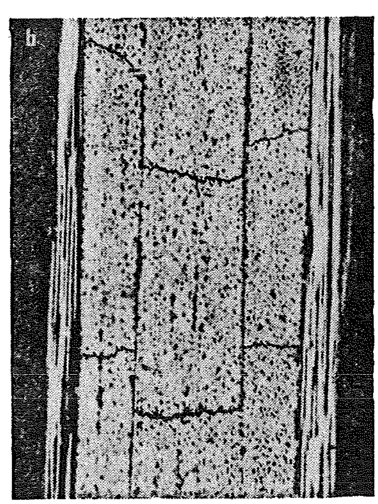
LAMINATE FRACTURE



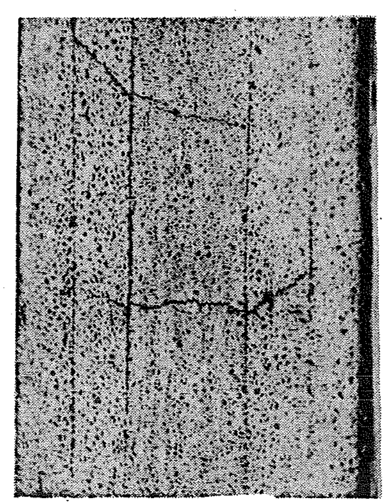
Stress-strain relations of $[0/\pm45/90]_s$ Gl/Ep and of constituent plies



$[0/90]_s$



$[0/\pm45]_s$

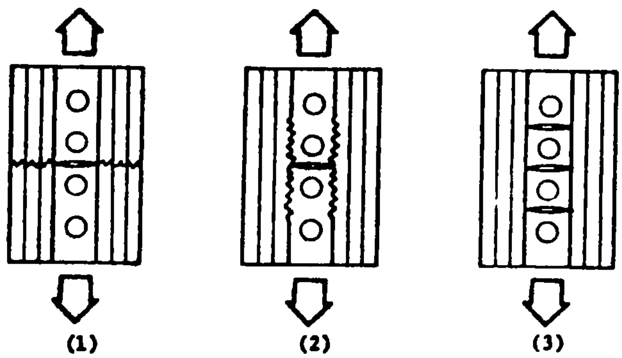


$[0/\pm45/90]_s$

Failure modes at free edge

Graphite/Epoxy T300/5208 $[0/90/\pm 45]_s$

Symbol	Maximum Stress ksi	Life N
⊡	50	793, 340
⊙	50	704, 870
●	60	37,560
■	60	52, 360
▲	60	23, 090
♦	60	24, 570
×	40	



Typical failure mechanisms of composite laminates - Mode (1) is the most catastrophic and mode (3) the most desirable